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Molecular Rayleigh scattering to measure fluctuations in density, velocity and temperature in wind tunnel applications
(Phase I)

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Goal

To advance Rayleigh scattering based measurement technique for application in wind tunnel environment

- Setup proof of concept systems to learn and overcome difficulties in wind tunnel applications

- Simultaneous measurements of fluctuations in velocity, temperature and density - up to 25kHz bandwidth

Motivation

- Every wind-tunnel needs to know the level of free-stream turbulent fluctuations – Do the existing transonic, supersonic, hypersonic wind tunnel know that number? Perhaps not.

- Lack of measurement tools for high speed flows
  - Need scalars T, ρ, P in addition to velocity **U**
  - Existing tools cannot measure fluctuations in T, ρ
    - PIV, LDV, hot-wire primarily measures **U**
    - Cannot measure turbulent stress: ρuu, ρvv etc; needs simultaneous measurement of ρ & **U**

- Experimental data on shock-waves and their unsteadiness hardly exist.

- Critical parameters for CFD validation, aero-acoustic modelling, heat- and mass transfer modelling cannot be measured.
  - ρ-U, T-U correlations, pressure-strain correlations etc
  - Frequency-wavenumber spectra of fluctuations in T, ρ, ρuu

Existing/ past Rayleigh efforts:

A. GRC/Universities - Jet noise source identification, heated and unheated transonic & supersonic jets

B. Studies of premixed H2-O2 flame etc.

Presentation Roadmap:

- Basics of aerodynamic measurement using Rayleigh scattering

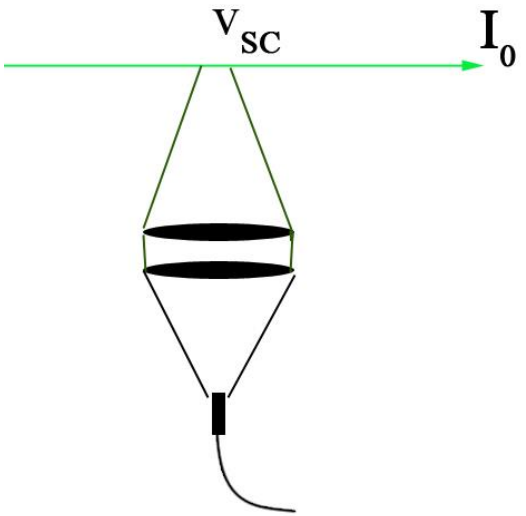
- Basics of air density measurement
- Bench-top setup created in the Fluid Mechanics Lab
- Measurement of density fluctuations spectra in a heated plume

- Basics of velocity and temperature measurement
- Setup of a spectroscope – progress made so far.

- Rayleigh setup in a low-speed Wind tunnel
  Application –boundary layer transition observed via density fluctuations

- Summary, Deliverable, Schedule

Basics: Aerodynamic Measurements via Molecular Rayleigh scattering of Laser light



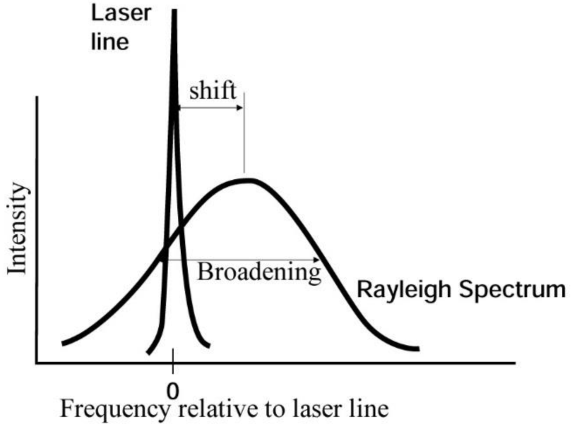
- A particle-free, non-intrusive technique to simultaneously measure density, temperature & velocity

- A laser beam is passed through the air-stream & light scattered by O_2 and N_2 molecules from points along the beam are collected and analyzed

- Air density from molecular num density
  - o Requires measurement of light intensity

- Air velocity from the shift in the spectral peak.
  - o Requires high-resolution spectral analysis of scattered light
  - o Needs single-mode laser

- Air temperature from the width of the distribution of molecular speed.



Density measurement using Rayleigh Scattering

$$\textit{Power of scattered light}\ P_S = m\, I_0\, V_{SC} \left(\sum_i \mu_i \frac{\partial \sigma_i}{\partial \Omega} \right) \sin^2 \chi\, d\Omega$$

molecular no density

Incident Light irradiance

Probe volume

Scattering cross-section

Angle from polarization plane

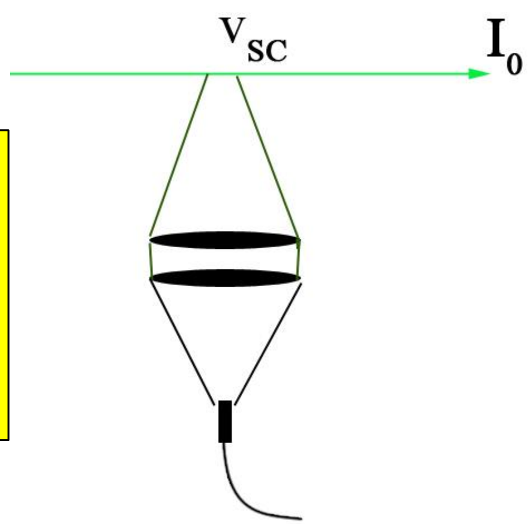
Collection solid angle

$$m = \frac{\rho\, N_A}{M}$$

$$\textit{\# of photoelectrons}\ N = \frac{\varepsilon\, \rho\, N_A\, I_0\, V_{SC} \left(\sum_i \mu_i \frac{\partial \sigma_i}{\partial \Omega} \right) \sin^2 \chi\, d\Omega\, \Delta t}{M\, h\, \nu} = k\, \rho\, \Delta t$$

- In absence of dust particles, in a constant composition gas mixture (air), the intensity of total scattered light is proportional to the local density

- Fluctuations in light intensity ~ fluctuations in air density



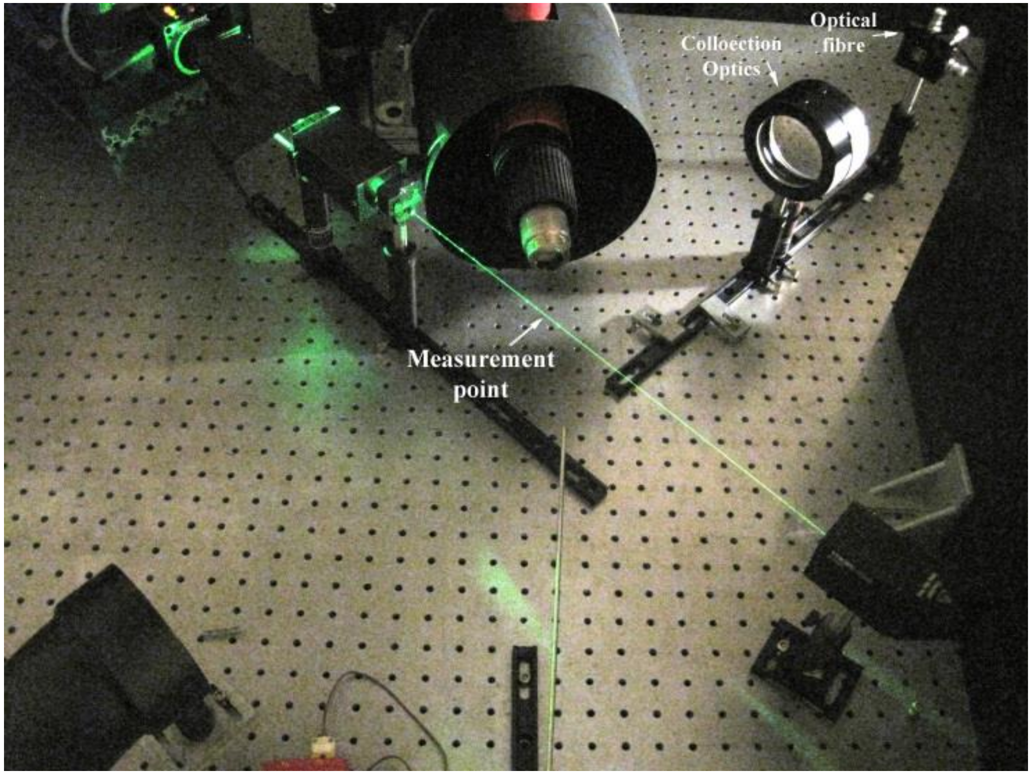
Challenges with implementation:

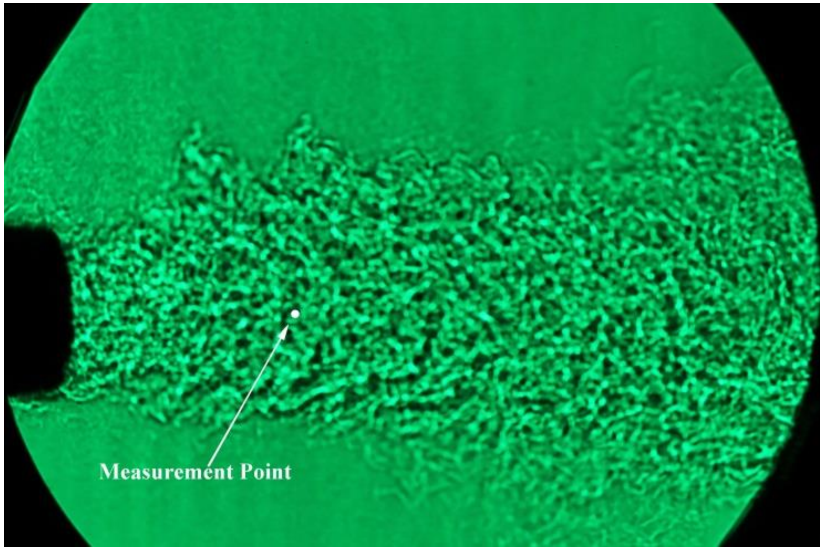
- Efficient removal of dust particles
  - o Rayleigh scattering cross-section at ambient condition:
    σ (N_2) =5×10^{-32} m^2; ~10^{15} molecules in probe vol
    Total scattering cross-section = 5×10^{-17} m^2
  - o σ (1 micron water droplet) ~10^{-16} m^2

Scattering from a single 1 micron particle
is stronger than the total molecular scattering

- Very low light intensity – photon counting and shot noise
- Suppression of background light
- Vibration isolation
- Design application specific optical setup

Bench top setup in a low speed hot plume

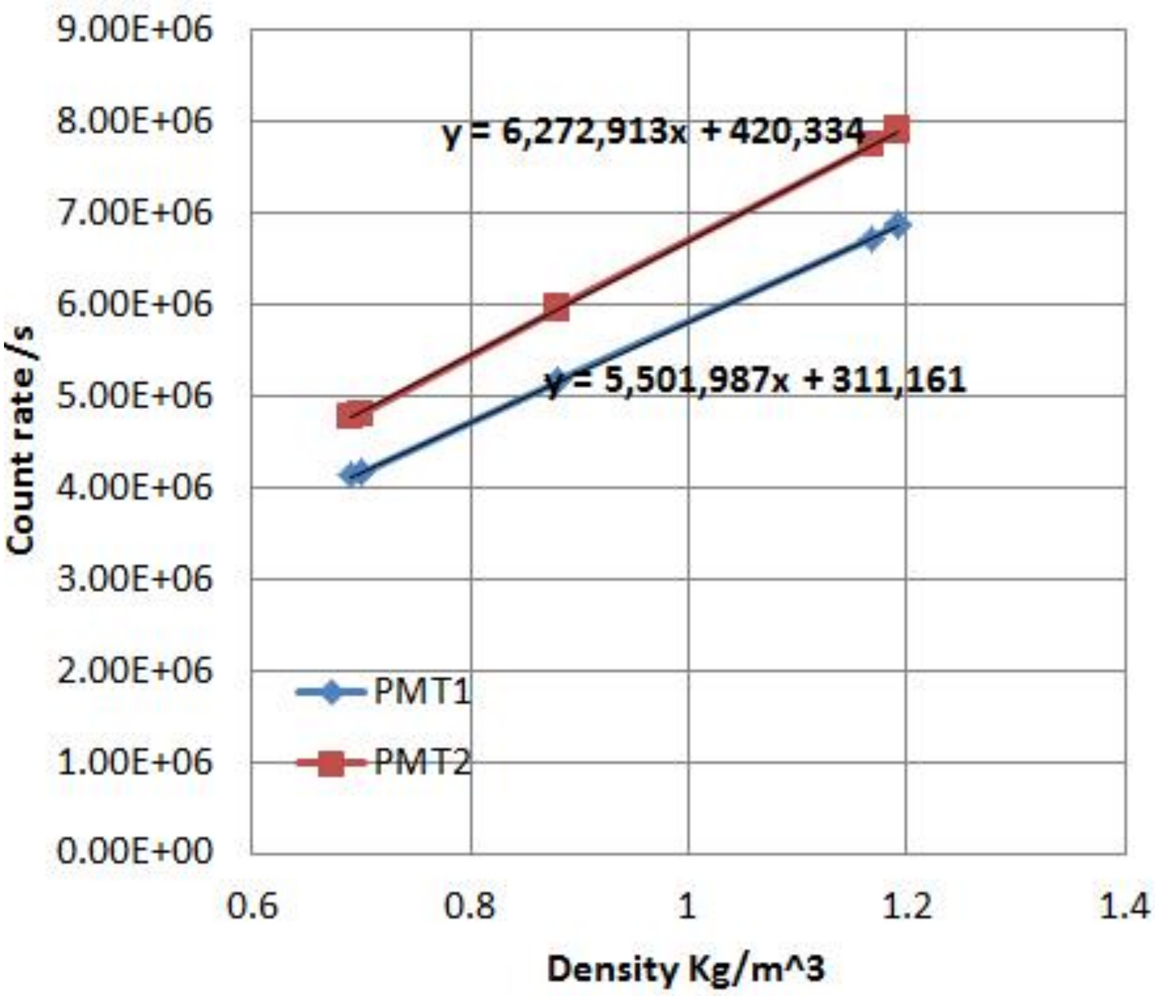




Shadowgraph of hot-plume and location of the probe volume

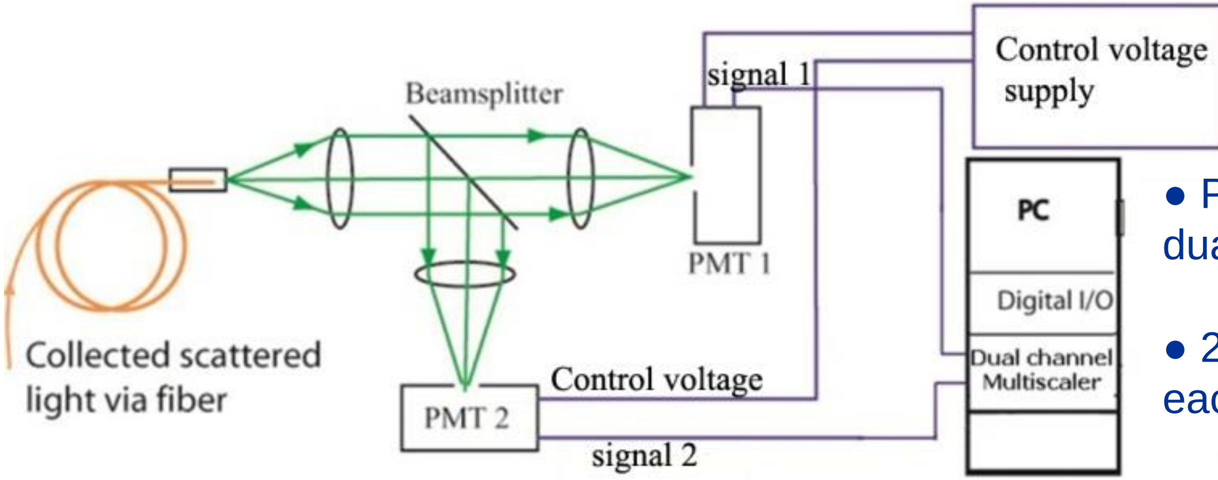
- Air flow cleaned by a HEPA filter
- Center hot plume from an electric heater
- Laser: Nd:VO_4 freq doubled to 532nm, CW, 2W
- f/4 collection optics
- 0.6 mm long probe volume along laser path

Density measurement
Calibration: count rate vs density, hot-plume setup

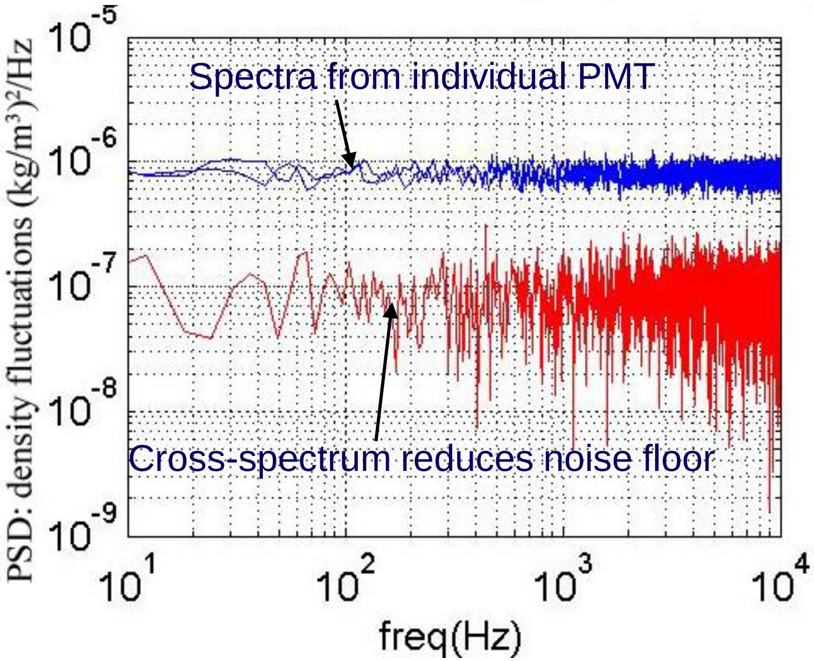


$$N_{av} = (a\,\rho + b)\,\Delta t\,, \quad \text{where } N_{av} = \frac{\Sigma N_i}{n}$$

Density fluctuations spectra:
Reduction of Electronic shot noise via 2-PMT cross-correlation technique



- Photo-electron counting using dual channel multi-scalar
- 262144 contiguous time bins each 20 to 50μ-s duration



Spectra from ambient (no fluctuations in density) air

Electronic shot noise is the primary source of uncertainty in spectral data

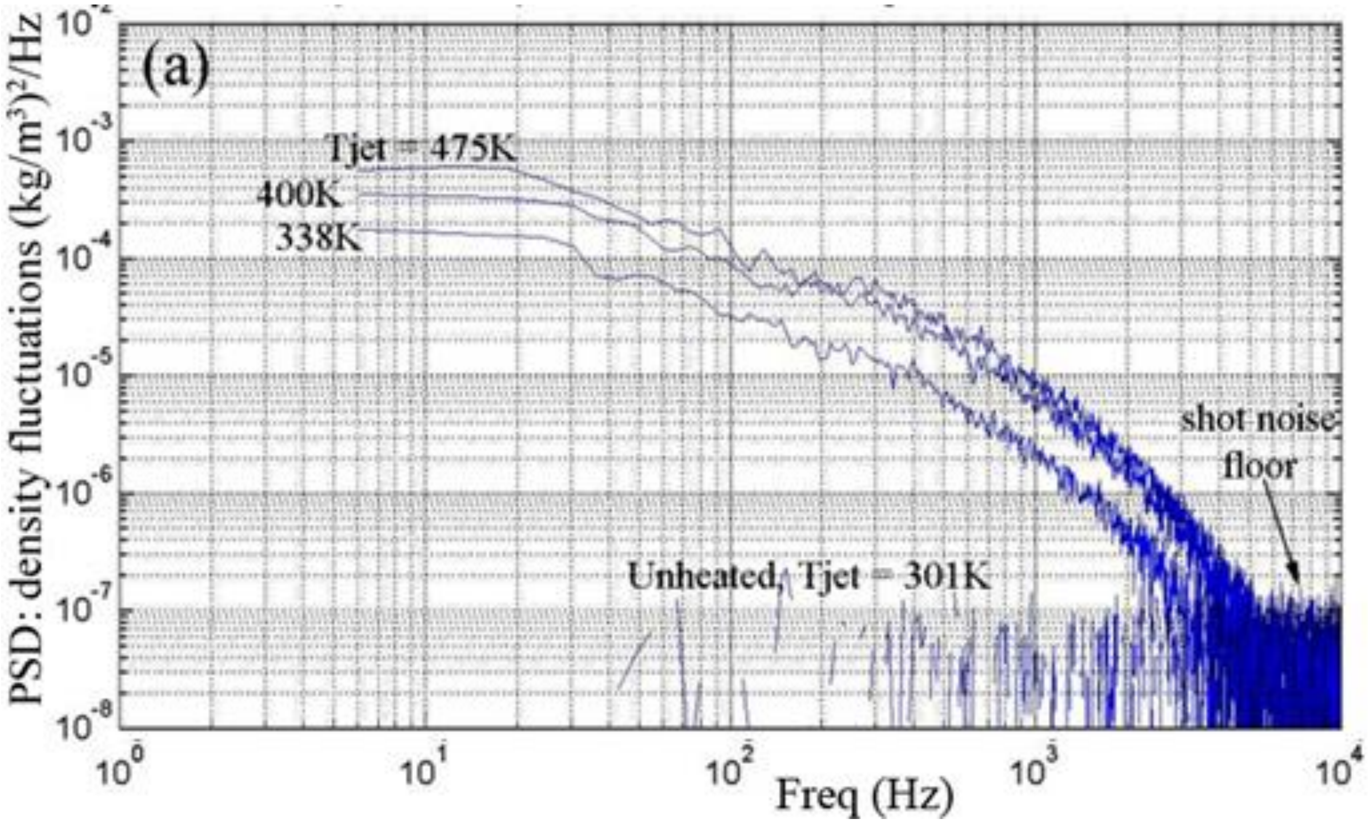
- Minimization using cross spectral density:

$$\left|P_{N_1' N_2'}(f_l)\right| = \frac{2}{n^2}\left|F_{N_1'}(l) \,.\, F_{N_2'}^{*}(l)\right| ,$$

- Density fluctuations spectra:

$$P_{\rho'^2}(f_l) = \frac{\left|P_{N_1' N_2'}(f_l)\right|}{a_1 a_2 (\Delta t)^2}$$

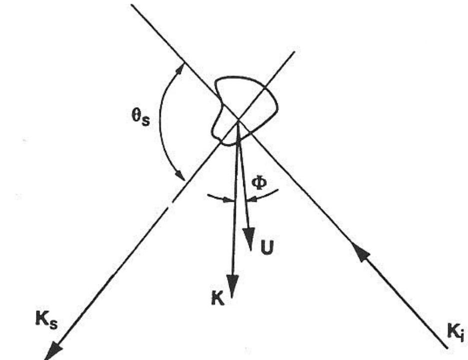
Density fluctuations spectra from hot plume of bench-top setup



- Spectra from plume centerline at indicated Temperatures

- **Excellent signal to noise ratio >10^4**

Measurement of Velocity and Temperature via Spectroscopic Analysis of Scattered Light



Scattering diagram to measure velocity

- Gas molecules in an airstream flowing with velocity U have a distribution of velocity, such as:

$$f(V)d^3V = \frac{n}{\pi^{\frac{3}{2}}a^3}\exp\left(-\frac{(V-U)^2}{a^2}\right)d^3V$$

$$a = \left(\frac{2k_BT}{m}\right)^{1/2}, \qquad T = gas\,Temperature$$

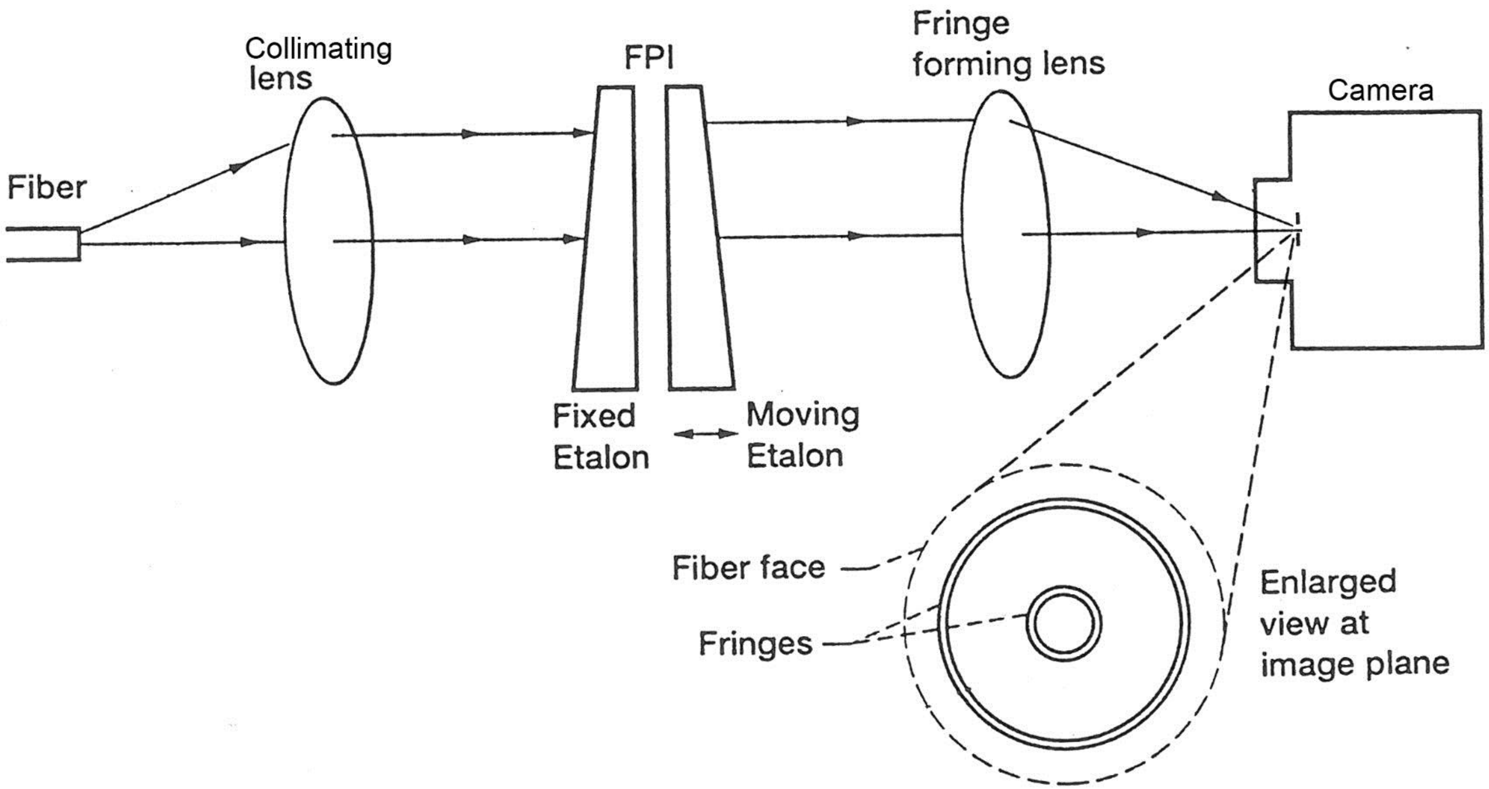
- Which manifests as a distribution of Doppler shift of incident light $f_d = \frac{k.U}{2\pi}$
- High resolution Fabry-Perot interferometer is used to measure Doppler shift.
- The Measured spectrum is a convolution of instrument function $I(\nu^/)$ and Rayleigh Spectrum $S_R(\nu - \nu^/)$

$$S_M(\nu) = G_R \int I(\nu^/) S_R(\nu - \nu^/) d\nu^/$$

- Significant modelling is required to extract velocity and temperature from Rayleigh spectrum

Measurement of Velocity and Temperature via Spectroscopic Analysis of Scattered Light

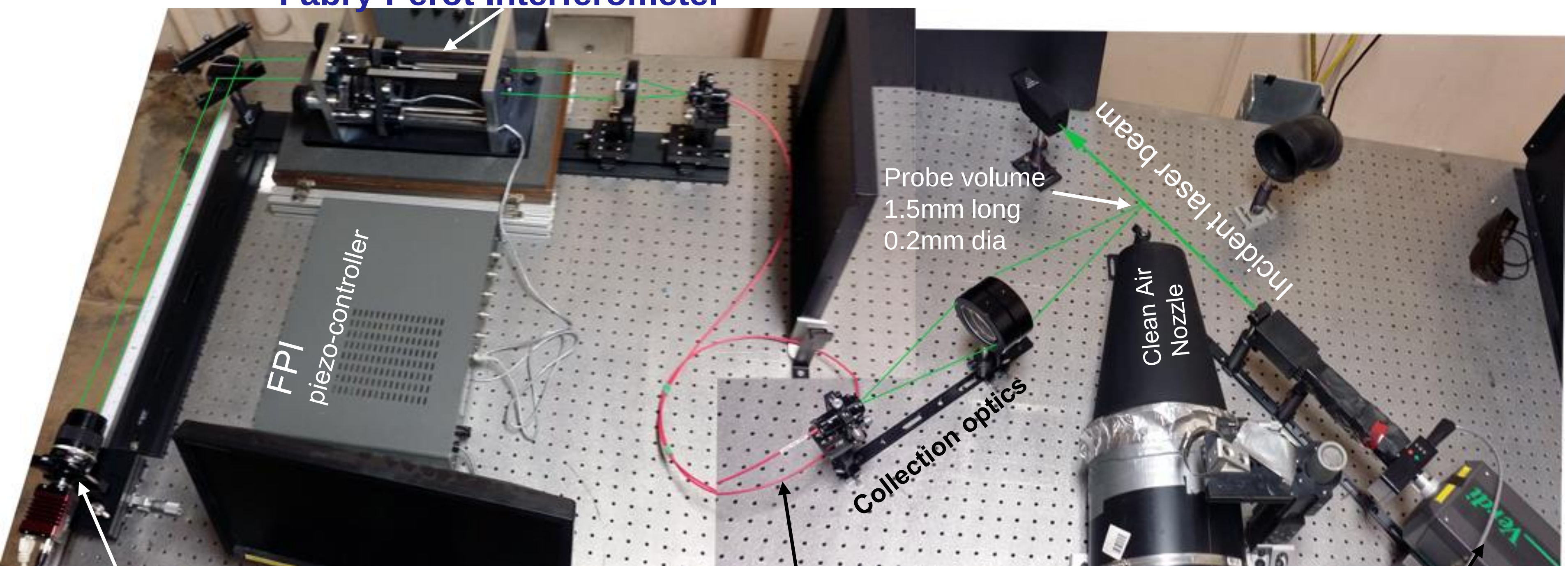
Fabry-Perot acts as a frequency dependent light filter



Fabry-Perot interferometer to spectrally resolve Rayleigh scattered light

- High resolution: FPI free-spectral range set to 7.5GHz

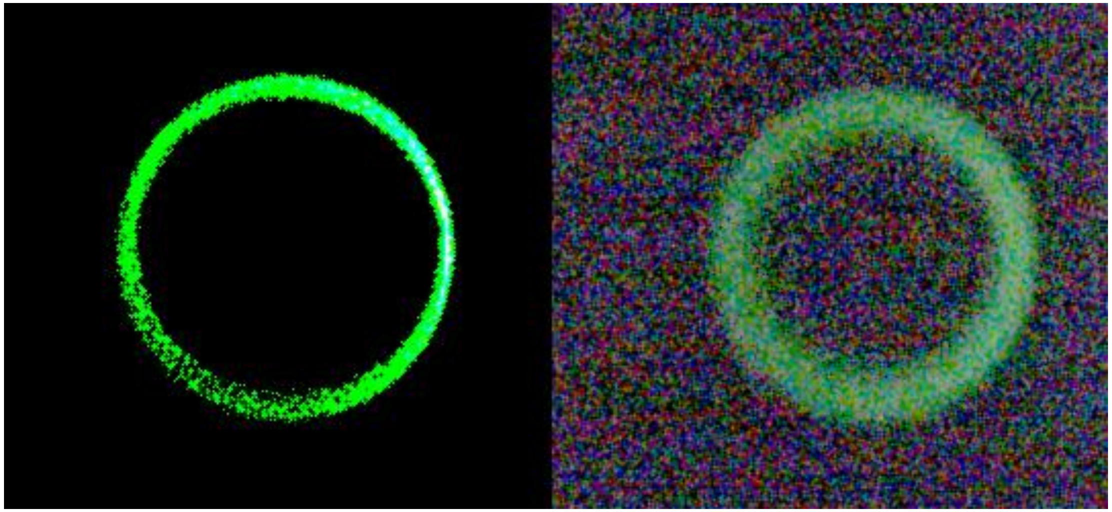
Spectroscopic setup to measure Velocity and Temperature



Setup at FML Test Cell I

- All optics (except Laser) and electronics were purchased using seedling fund

Spectroscopic setup to measure Velocity and Temperature

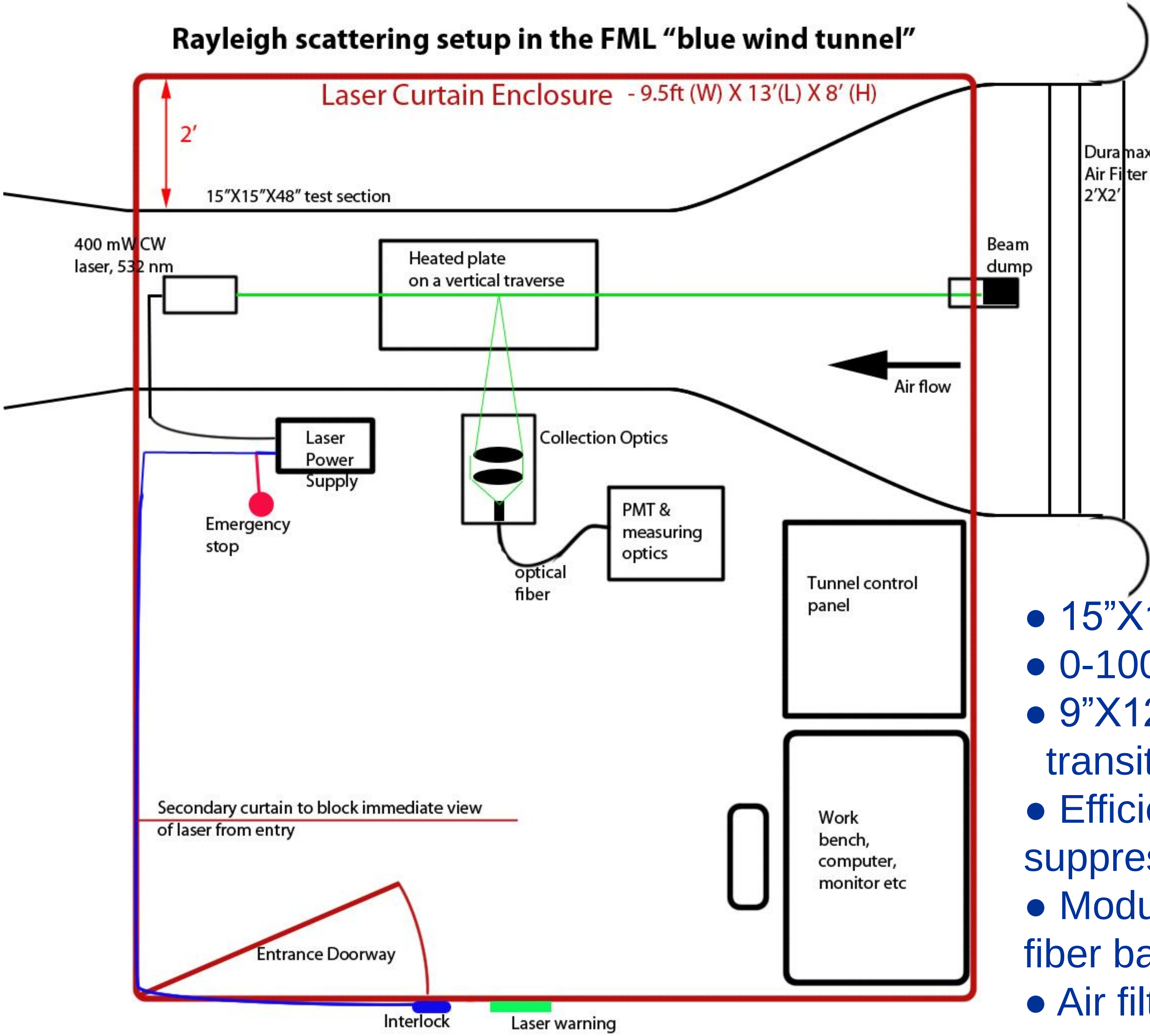


Reference spectrum of incident laser

Spectrum of **Rayleigh scattered light**
- Fairly noisy

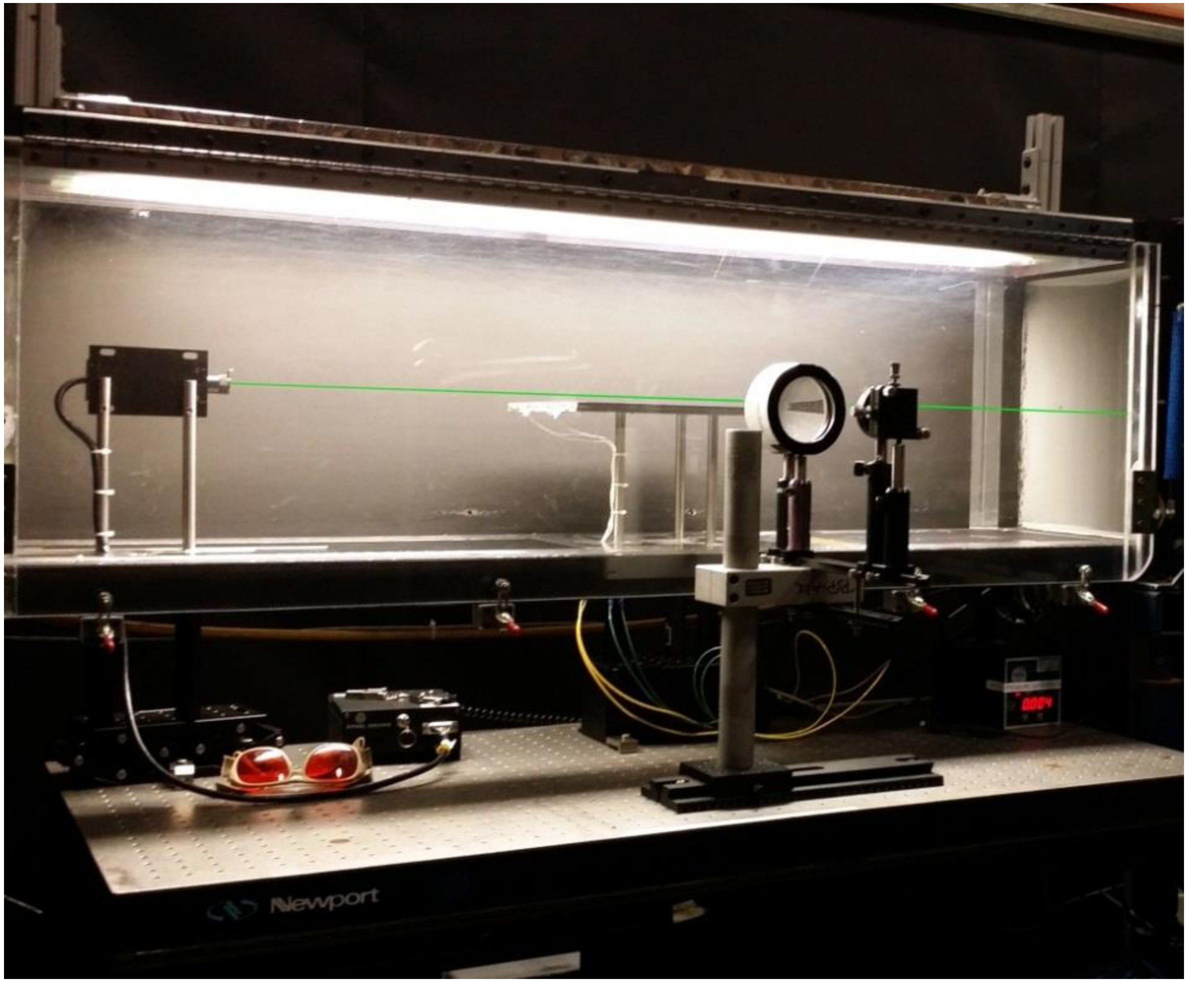
Work in progress - future work:
1. Buy /borrow low noise (cooled), high-speed camera
2. Software to establish Rayleigh spectra from optical fringes – big job!
3. Stabilization of Fabry-Perot
4. Measure time-average Rayleigh spectra – Time averaged U, T
5. Measure unsteady Rayleigh spectra – Fluctuating U, T

Setup in a Low-speed wind tunnel



- 15"X15"X48" test section
- 0-100 ft/s flow
- 9"X12" heated flat plate for transition study
- Efficient background suppression
- Modular design – optical fiber based
- Air filtration at inlet

Setup in a Low-speed wind tunnel

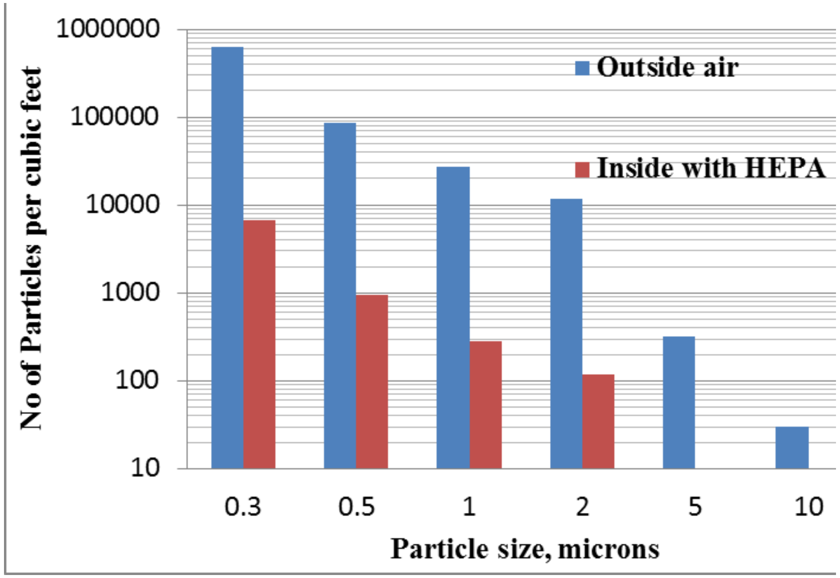


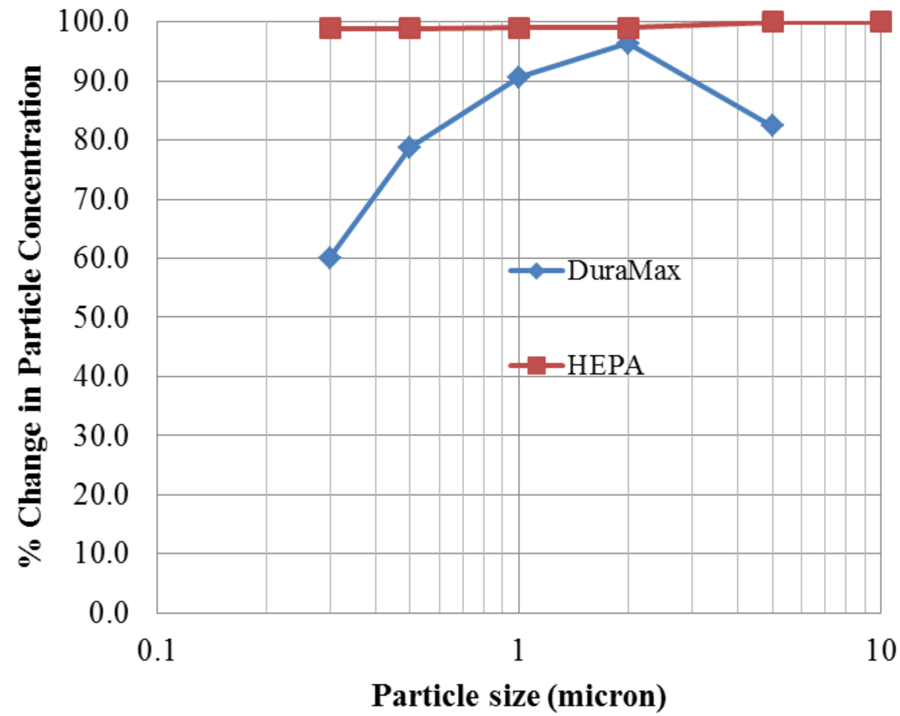
Setup to study boundary-layer transition over a heated plate

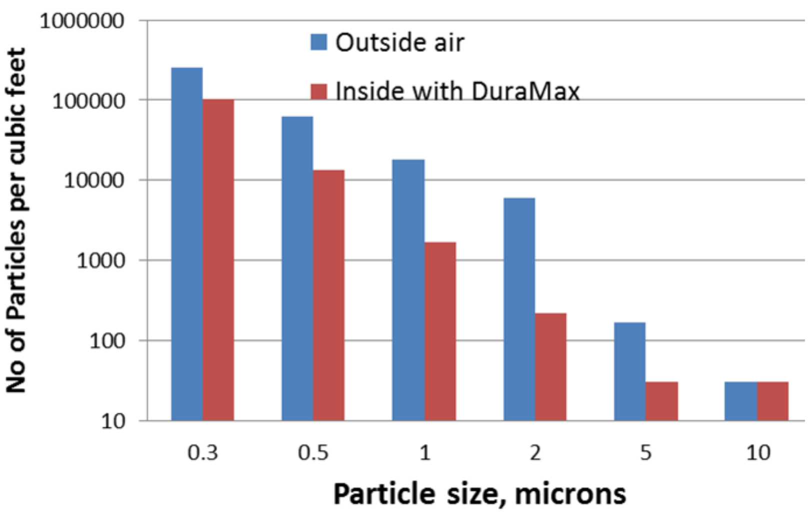
Air filter at tunnel inlet for dust removal

- airflow restriction
- Large filter-box for higher speed.

Dust removal from wind tunnel air stream
Measurement of particle concentration

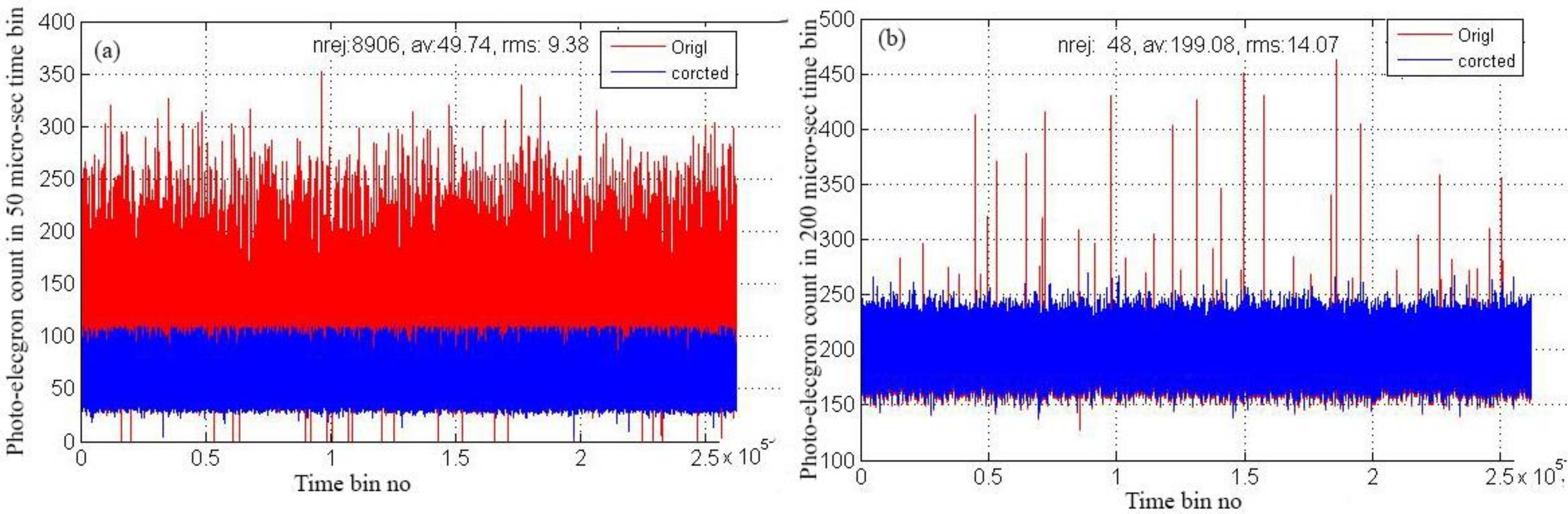






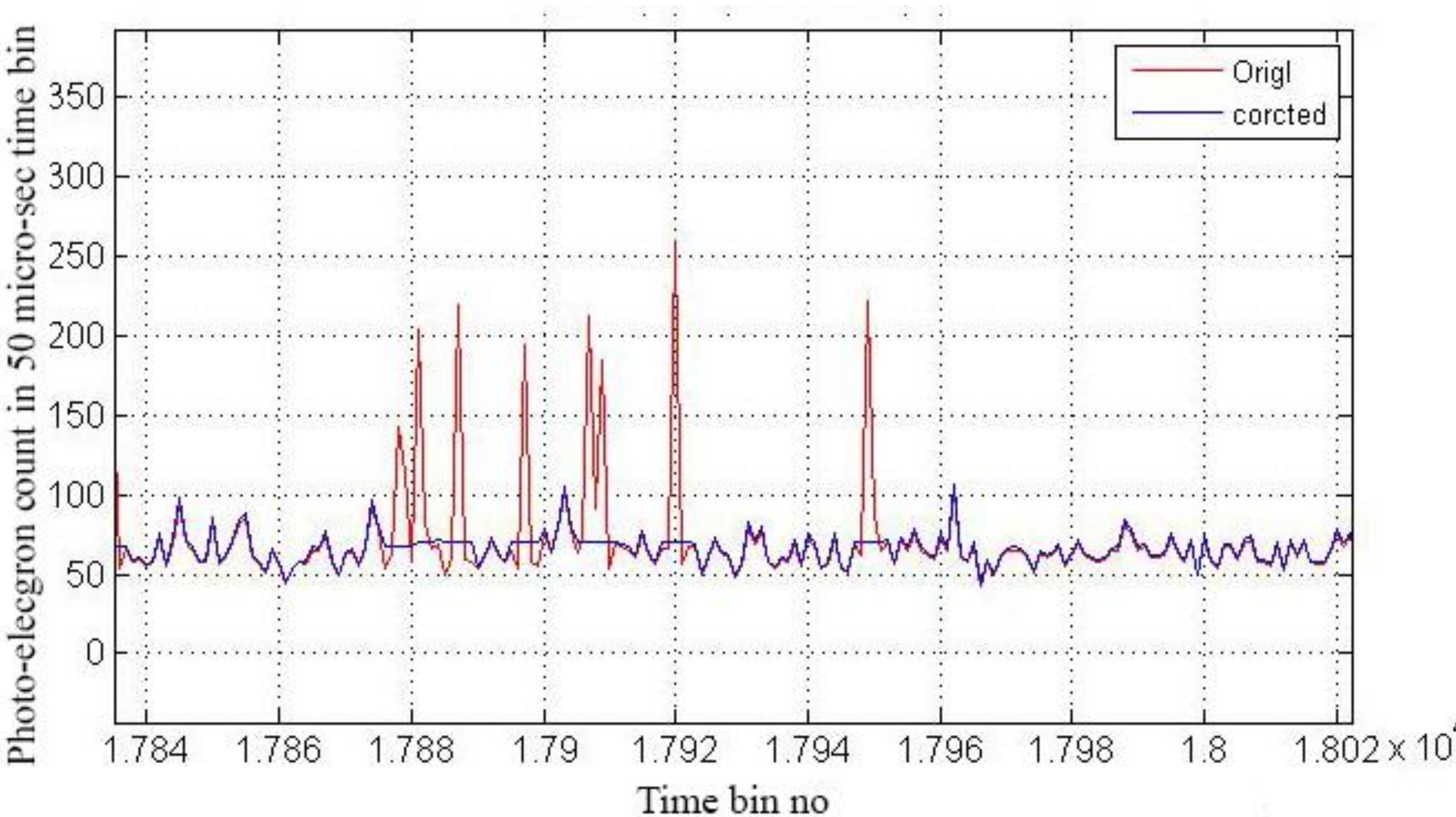
- Experimentation with different types of air filters were
- HEPA filters provide sufficient cleaning

Impact of Dust Particles on Rayleigh Signature

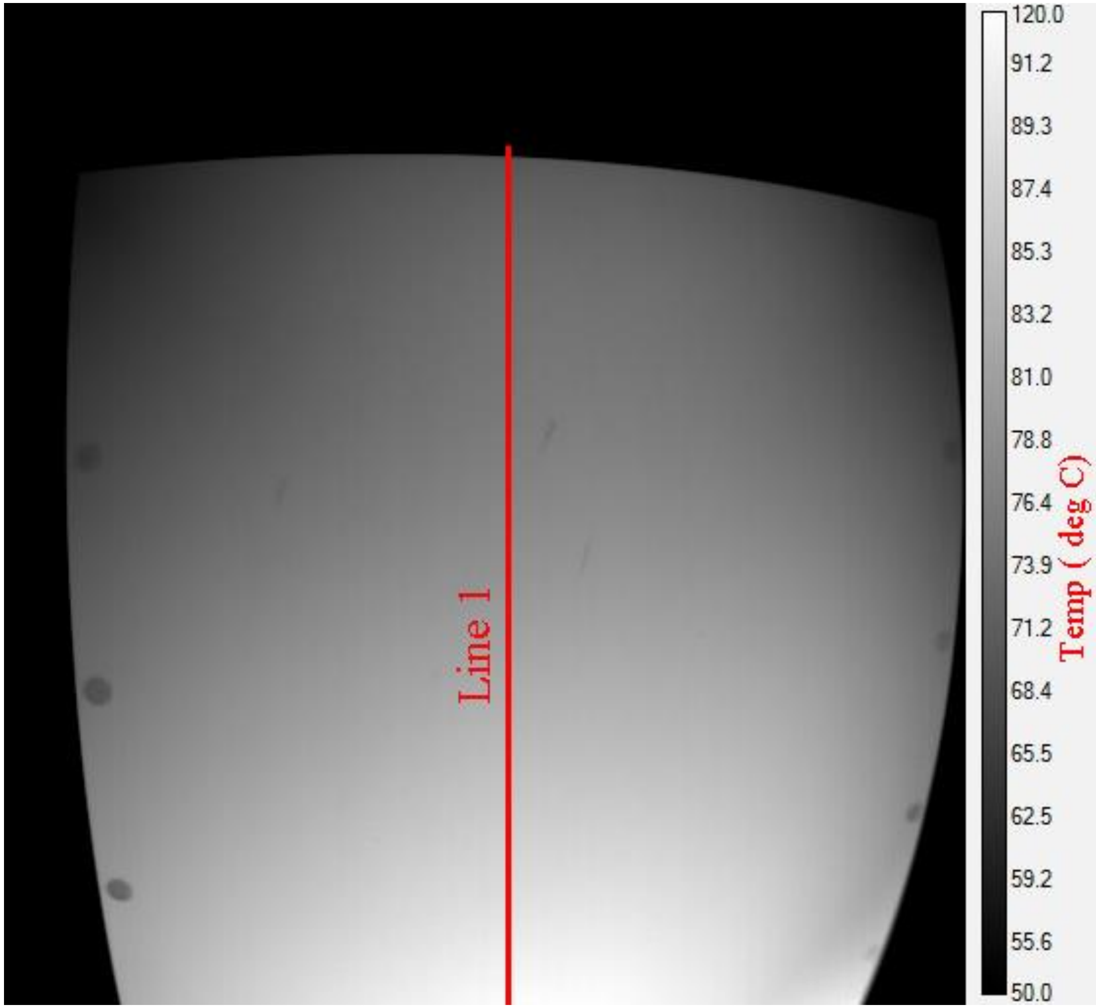


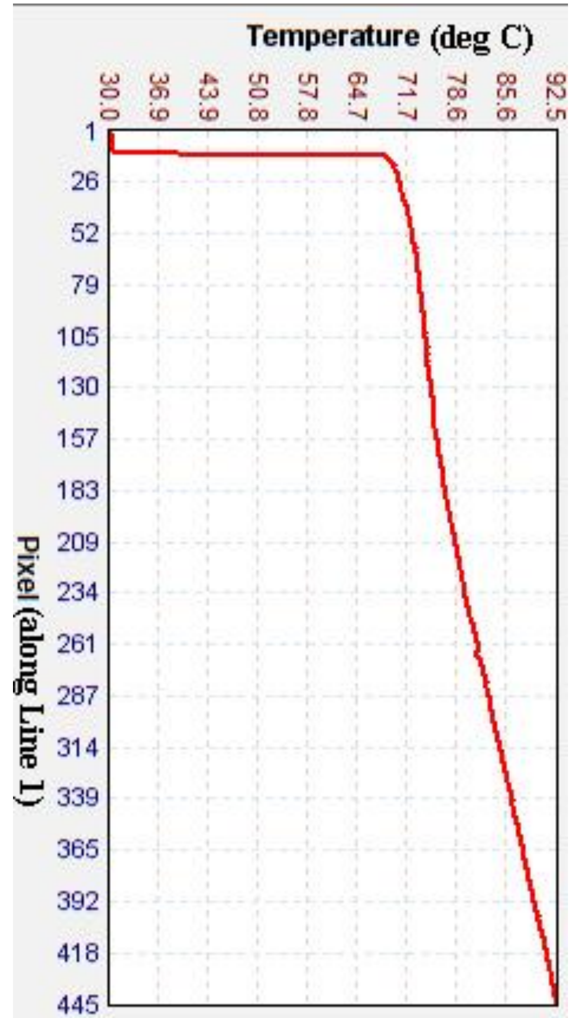
Software Removal of Particle Signature

$$If\ \ N_i \geq kN_{stddev}\ \ N_i = N_{av}\,, \qquad k = 5$$



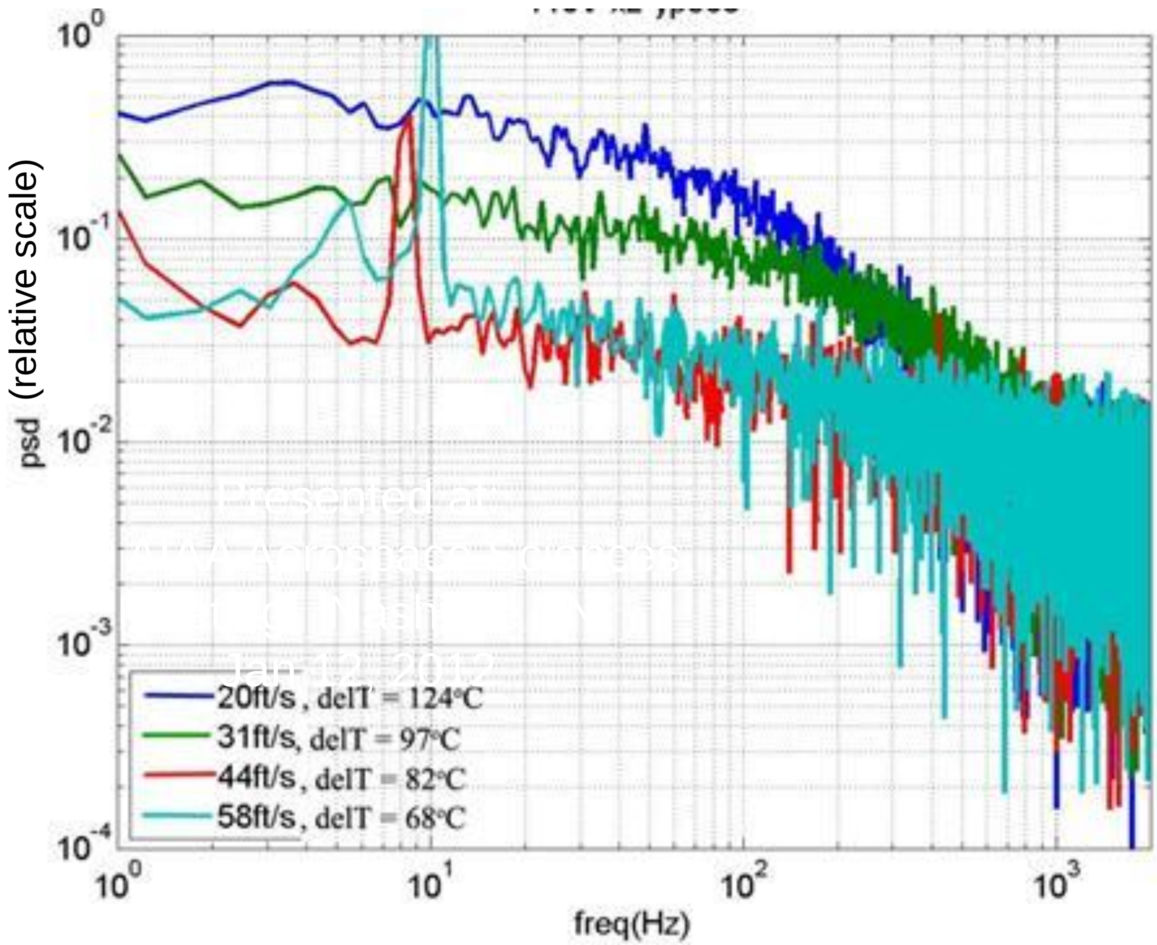
Heated flat plate in wind tunnel
Temperature distribution measured by an IR camera





- 60ft/s flow, ~600W heat flux on a 9"X12" plate
- Possible laminar separation due to sharp leading edge
- Currently modifying the leading edge to elliptical shape

Density fluctuation spectra from heated flat plate



- *Probe location: x=2" from leading edge, y=0.065" from plate surface.*
- vibration of Laser mount – spurious tones

- **Nevertheless, spectral levels rise by a factor of 100 over the noise floor**

Work in progress:
1. Reduce tunnel vibration
2. Detailed Survey of density spectra for boundary-layer transition
3. 2-point and multi-point space-time correlation of density fluctuations
4. Spectroscopic setup to measure temperature profiles

Summary

- Started from scratch - first time setup at ARC
    - Except for the laser, all optics and electronics were purchased, optical train designed, and implemented.

- Progressed towards two working setup:
    - Bench-top system around a clean jet
        - Working system to measure density fluctuations spectra
        - Work in progress: Spectroscopic setup to resolve Rayleigh spectra for velocity and temperature measurement
    - A low-speed wind tunnel setup
        - Overcame problems with aerosol contaminations, surface proximity
        - A two-PMT cross-correlation system and photo-electron counting was used for density fluctuations spectra
        - Spectra of density fluctuations show high signal-to-noise ratio:10^2 - 10^4
        - Work in progress – Study boundary layer transition via density fluctuations – *possible for the first time due to the present advancement*

We are thankful to the ARMD Seedling program to help “germinate” a new Rayleigh setup for wind tunnel applications.

Programmatic: Product & Deliverables

- Duration Feb. 2013 – Aug 2014 (6 month extension)
- Start – end TRL: 1- 4

- **Products:**

(a) Hardware and software to measure density fluctuations spectra. Apr 2014✓
(b) Preliminary hardware setup for spectroscopic analysis to perform velocity and temperature measurements. Aug 2014✓

- **Deliverables and schedule:**

(a) Design of the Rayleigh system & component procurement Jun 2013✓
(b) Proof-of-concept demonstration in a heated free-jet Aug 2013✓
(c) Cleaning of a research wind tunnel in FML, verification of operation Feb 2014✓
(d) Proof-of-concept demonstration in a subsonic wind tunnel at FML Apr 2014✓
(e) Spectroscopic setup for velocity & temperature measurements Aug 2014 (in progress)

- Forward support: Effort continuing under Transformative Aeronautics Concepts Program (Tools and Methods)
  – Not part of this presentation